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REDUNDANCY AND THE CHOICE OF HYDROLOGIC INDICES FOR CHARACTERIZING STREAMFLOW REGIMES

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ABSTRACT

The utility of hydrologic indices for describing various aspects of streamflow regimes has resulted in their increased application in riverine research. Consequently, researchers are now confronted with the task of having to choose among a large number of competing hydrologic indices to reduce computational effort and variable redundancy prior to statistical analyses, while still adequately representing the major facets of the flow regime. The present study addresses this concern by providing a comprehensive review of 171 currently available hydrologic indices (including the commonly used Indicators of Hydrologic Alteration) using long-term flow records from 420 sites from across the continental USA. We highlight patterns of redundancy among these hydrologic indices and provide a number of statistically and ecologically based recommendations for the selection of a reduced set of indices that can simultaneously (1) explain a dominant proportion of statistical variation in the complete set of hydrologic indices and (2) minimize multicollinearity while still adequately representing recognized, critical attributes of the flow regime. In addition, we examine the transferability of hydrologic indices across ‘stream types’ by identifying indices that consistently explain dominant patterns of variance across streams in varying climatic and geologic environments. Together, our results provide a framework from which researchers can identify hydrologic indices that adequately characterize flow regimes in a non-redundant manner. In combination with ecological knowledge, this framework can guide researchers in the parsimonious selection of hydrologic indices for future hydroecological studies. Copyright © 2003 John Wiley & Sons, Ltd.

KEY WORDS: hydrology; dams; alteration; variability; indicators

INTRODUCTION

The natural flow paradigm emphasizes the need to partially or fully maintain or restore the range of natural intra- and interannual variation of hydrologic regimes in order to protect native biodiversity and the evolutionary potential of aquatic, riparian and wetland ecosystems (Arthington *et al*., 1991; Sparks, 1992; Richter *et al*., 1996, 1997; Stanford *et al*., 1996; Poff *et al*., 1997). A number of ecologically important streamflow characteristics constitute the natural flow regime, including the seasonal patterning of flows; timing of extreme flows; the frequency, predictability, and duration of floods, droughts, and intermittent flows; daily, seasonal, and annual flow variability; and rates of change (Poff *et al*., 1997). Assessment of these streamflow characteristics is essential for understanding and predicting the biological impact of both natural and altered flow regimes on riverine biota. For instance, the potential influence of impoundment (e.g. Ward and Stanford, 1995), interbasin transfers (e.g. Davies *et al*., 1992) and groundwater abstraction (e.g. Owen, 1991) on streamflow regimes must be accurately quantified in order to establish instream hydrological and ecological management targets (Petts *et al*., 1995). Accordingly, researchers have developed and applied a number of hydrologic indices in attempts to characterize different components of the flow regime.

The development of hydrologic indices in river ecology was motivated with a number of different goals in mind. Indices have been developed to characterize particular regions in terms of biologically relevant flow variables, describe overall variability in regional or global hydrologic regimes, and to quantify flow characteristics that are believed to be sensitive to various forms of human perturbation. The overarching

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goal of streamflow characterization and classification has been to develop hydrologic indices that account for characteristics of streamflow variability that are 'biologically relevant', i.e. that are believed important in shaping ecological processes in streams. However, given the multitude of different ways in which streamflow can be characterized, researchers have taken a variety of approaches. Early studies focused on average flow conditions (Hawkes *et al*., 1986; Moss *et al*., 1987; Townsend *et al*., 1987), variation in mean daily flow (Horwitz, 1978), predictability of flows (*sensu* Colwell 1974; e.g. Bunn *et al*. 1986; Resh *et al*. 1988; Gan *et al*. 1991), skewness in flow and peak discharges (Jowett and Duncan, 1990), short-term estimates of flood frequency (Cushing *et al*., 1983; Minckley and Meffe, 1987), slopes of flood-frequency curves (Farquharson *et al*., 1992), seasonal distributions of monthly flows (Haines *et al*., 1988), flow and flood frequency duration curves, and time series of annual discharge (McMahon *et al*., 1992). More recent investigations have begun to focus on examining suites of hydrologic indices simultaneously (e.g. Hughes and James, 1989; Poff and Ward, 1989; Poff and Allan, 1995; Poff, 1996; Richter *et al*., 1996, 1997, 1998; Clausen and Biggs, 1997, 2000; Puckridge *et al*., 1998; Extence *et al*., 1999; Wood *et al*., 2000; Pettit *et al*., 2001), thus taking a multivariable approach to quantifying the hydrologic regime.

Interestingly, although the use of single hydrologic indices in streamflow characterizations has been criticized for being overly simplified and lacking adequate biological relevance (e.g. Poff, 1996; Richter *et al*., 1996, 1997), stream ecologists are now faced with the difficult task of choosing from the plethora of available hydrologic indices. For example, the Indicators of Hydrologic Alteration (IHAs: Richter *et al*., 1996) approach is commonly used for characterizing human modification of flow regimes, yet it contains 33 individual metrics (and 33 associated measures of variation), many of which are intercorrelated. To date, researchers and managers have been provided with little guidance regarding the question: Which minimum subset of available hydrologic indices is required to adequately describe the main aspects of the flow regime? An answer to such a question would be an important contribution to the field of river research because it would provide investigators with a means of identifying a parsimonious set of hydrologic indices that represent critical streamflow characteristics and adequately represent the available information provided by the population of indices that have been developed.

In this study, we undertake a comprehensive review of the currently available hydrologic indices for characterizing streamflow regimes. Using long-term flow records from 420 locations across the continental USA representing streams with varying climatic and geologic conditions, we highlight patterns of redundancy among these indices to aid researchers in parsimonious selection of indices in future hydroecological studies. There are three main objectives of this paper. First, we examine 171 published hydrologic indices to search for a reduced set of indices that can simultaneously explain a dominant proportion of statistical variation in the complete set of hydrologic indices and adequately represent recognized, critical attributes of the flow regime. Second, given that expertise in computer programming is required to calculate the majority of the hydrologic indices, we examine the effectiveness of the Indicators of Hydrologic Alteration (which can be calculated using commercially available software) to adequately represent the variation provided by the entire set of hydrologic indices. Third, we assess the transferability of the indices by identifying indices that consistently explain dominant patterns of variation for 'stream types' having obviously different streamflow characteristics. By addressing each of these objectives, we provide statistically sound recommendations on which hydrologic indices can be used to adequately characterize flow regimes in a non-redundant manner, which we hope will facilitate some standardization in future hydroecological analyses.

METHODS

Hydrologic indices

We examined a total of 171 hydrologic indices from 13 published papers (Hughes and James, 1989; Poff and Ward, 1989; Richards, 1989, 1990; Poff, 1996; Richter *et al*., 1996, 1997, 1998; Clausen and Biggs, 1997, 2000; Puckridge *et al*., 1998; Clausen *et al*., 2000; Wood *et al*., 2000), where the indices were derived to represent biologically relevant streamflow attributes (see Appendix). Techniques associated with environmental flow assessment methods designed to evaluate flow needs for specific rivers (e.g. Building Block Methods or DRIFT: Brown and King, 2000) were not included. To aid in the description of the indices and facilitate comparisons among different components of the flow regime, we grouped the 171 hydrologic indices into five categories following Richter *et al*. (1996) and Poff *et al*. (1997). These included the magnitude ($n = 94$), frequency ($n = 14$), duration ($n = 44$), timing ($n = 10$) and rate of change ($n = 9$) in flow events, where magnitudes were subsequently divided into average ($n = 45$), low ($n = 22$) and high ($n = 27$) categories, frequency into low ($n = 3$) and high ($n = 11$) categories, and duration into low ($n = 20$) and high ($n = 24$) categories. This classification produced a total of nine subcategories of hydrologic indices designed to describe different facets of the streamflow regime. A variety of approaches could be used to assign individual indices to flow categories. We grouped indices of both central tendency and dispersion within subcategories. For example, mean daily flow is one index of 'average magnitude'. Daily flow values over the period of record comprise a distribution, which can be characterized according to statistical moments, including central tendency (mean) and dispersion (variance) (*sensu* Sokal and Rohlf, 1995). Therefore, we include both the index for mean daily flow and the index for coefficient of variation of daily flow in this subcategory.

All indices were calculated from daily mean flow records using a combination of computer macros written in the MatLab programming language (written by the authors) and the SAS programming language (written by Hans L. Iversen and Niels B. Ovesen, National Environmental Research Institute, Silkeborg, Denmark), and Indicators of Hydrologic Alteration software (Smythe Scientific Software, Boulder, Colorado, USA).

Streamflow data

Daily streamflow data for 420 sites across the contiguous USA were acquired from the US Geological Survey Water Resources database (http://water.usgs.gov/; Figure 1). These are the same sites analysed in Poff (1996), and they were selected to exhibit the following characteristics: (1) little or no flow regulation; (2) little or no catchment urbanization; (3) an accuracy rating of 'good' or 'better' for almost the entire record of flow values; and (4) catchment area $\leq$5000 km^2. The flow data consisted of a common 36 years record of continuous daily flow values from 1 October 1949 to 30 September 1985, representing a period of record in excess of the 20 years commonly used to ensure stable estimates of streamflow predictability (Gan *et al*., 1991). The names and locations of the stream gauge sites are contained in Poff and Allan (1993), and statistical summaries are presented in Poff (1996).

These streams occur across a wide geographic domain and therefore are located in many different climatic and geologic settings. This heterogeneous set of streams was classified into more regionally homogeneous groups that ranged from perennial to intermittent and from temporally stable to flashy based on a suite of ten hydrologic indices (Poff, 1996). In this study, we reduced the ten stream types of Poff (1996) into six distinctive stream types, to capture a range of types of streamflow regimes that occur around the world. We do not argue that these streamflow types are universal, or even most characteristic of global patterns; rather, they simply represent a range of flow regime types for which high quality data are available and thus they can be used to assess the degree of intercorrelation among the 171 hydrologic indices in a reasonable range of regional flow regime types. The six types are harsh intermittent ($n = 7$), intermittent flashy or runoff ($n = 30$), snowmelt ($n = 22$), snow and rain ($n = 56$), superstable or stable groundwater ($n = 72$), and perennial flashy or runoff ($n = 233$) (Figure 1).

Statistical analyses

Principal component analysis (PCA) extracted from the 171-by-171 correlation matrix (i.e. 171 hydrologic indices) was employed to examine dominant patterns of intercorrelation among the hydrologic indices and identify subsets of indices that describe the major sources of variation while minimizing redundancy (i.e. multicollinearity). The PCA was conducted using the correlation matrix rather than the covariance matrix because we were solely interested in examining relationships among the hydrologic indices and not the clustering of streams. In addition, by using the correlation matrix, we ensured that all indices contributed equally to the PCA and that these contributions were scale-independent (Legendre and Legendre, 1998). Separate PCA were performed using streamflow data for all streams and for each of the six stream types. Statistically significance of the principal-component axes was evaluated using the broken-stick rule, where

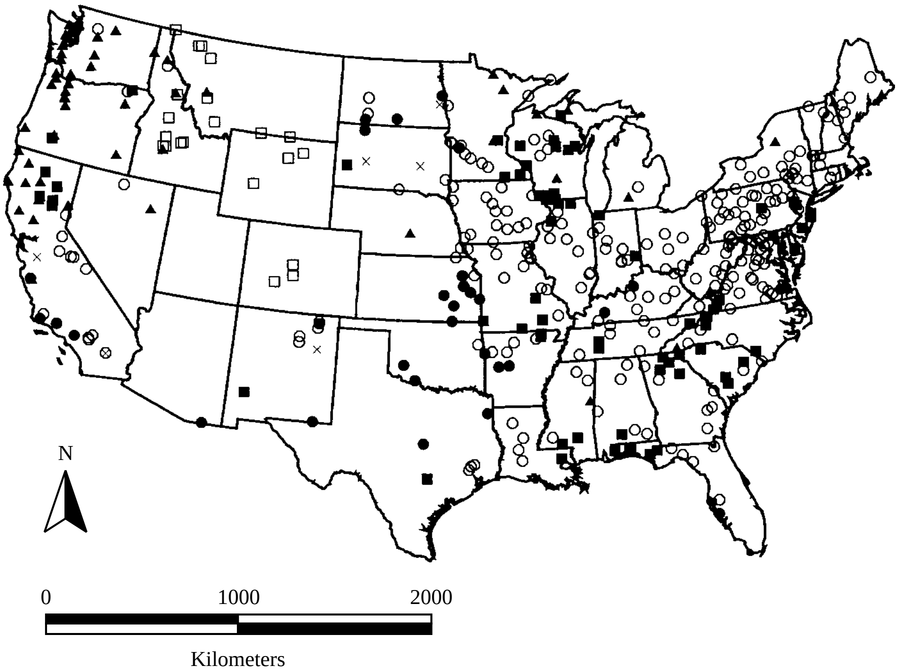

Figure 1. Locations of the 420 gauged streams representing six stream types (based on the hydrogeographic classification scheme of Poff, 1996): harsh intermittent (×), intermittent flashy or runoff (●), snowmelt (□), snow and rain (▲), superstable or stable groundwater (■), and perennial flashy or runoff (○)

the observed eigenvalues are compared to eigenvalues from random data (see Jackson (1993) for more details). Loadings of the original hydrologic indices on each significant principal component were used to identify indices that explain dominant patterns of variation provided by the entire pool of 171 indices. In addition, because principal-components axes by definition are orthogonal, we selected indices from different principal-component axes to ensure that the chosen indices are relatively independent from one another.

To test whether similar inter-relationships existed among the 171 hydrologic indices within each stream type, we made pair-wise comparisons among the stream type correlation matrices using the Mantel test (Legendre and Legendre, 1998). The Mantel test is an extension of a simple Pearson-moment correlation (ranging from -1 to $+1$), where the degree of concordance between two similarity matrices (here, 171-by-171 correlation matrices for n streams in each stream type category) is quantified. Given that the hydrologic indices are not independent (the same hydrologic indices were calculated for each stream type), statistical significance tests are not appropriate. Therefore, we qualitatively interpreted the relative magnitudes of the Mantel r statistics to assess the degree to which the inter-correlations among the hydrologic indices were similar among the different stream types, and thus to determine whether similar sets of indices could be universally applied, i.e. the degree of transferability.

RESULTS

General patterns of redundancy among hydrologic indices

The results from the PCA are presented in Table I, where the number of statistically significant principal-component axes ranged from two to four and together explained 75.7% of the variation for all streams combined and from 90.5 to 97.2% for the six stream types. Figure 2 presents the two-dimensional ordination illustrating the major patterns of inter-correlation among the 171 hydrologic indices for the combined set of 420 streams. Note that the correlation between any two indices is related to the cosine of the angle between their index-axes, i.e. between the vectors joining the origin and the index positions in Euclidean space, and

Table I. Results from the principal component analysis on the correlation matrix of the 171 hydrologic indices (see Appendix) based on 420 sites divided into six distinctive stream types (based on the hydrogeographic classification scheme of Poff, 1996)

	Principal component (% variation explained)				Total
	I	II	III	IV	
Intermittent					
Harsh intermittent	66.9	19.2	11.1	—	97.2
Intermittent flashy or runoff	48.2	24.1	15.7	5.8	93.8
Perennial					
Snowmelt	88.7	5.3	—	—	94.0
Snow and rain	82.6	12.5	—	—	95.1
Superstable or stable groundwater	63.8	24.8	4.3	—	92.9
Perennial flashy or runoff	66.6	14.4	9.5	—	90.5
All streams	39.1	22.8	7.7	6.1	75.7

Note that only the statistically significant principal components are reported. 'Total' refers to the total amount of variation explained by the significant principal components.

not the proximity between the apices of their axes, i.e. the distance between the index locations in Euclidean space. Therefore, two indices separated by a small angle (e.g. M_A3 and M_A4 with high loadings on PC I: Figure 2) are highly positively correlated; two indices separated by a large angle (e.g. R_A6 and R_A7 with opposite loadings on PC II: Figure 2) are highly negatively correlated; and, two indices separated by a right angle (e.g. T_A1 and T_A3: Figure 2) are uncorrelated or independent.

Figure 2 demonstrates that the degree of correlation among the hydrologic indices varies greatly, although the majority of indices are highly inter-correlated (either positively or negatively). A large number of indices are situated in the upper left and upper right quadrants of Figure 2, illustrating that within these two quadrants the variables are highly positively correlated, while variables in these different quadrants are negatively correlated. The upper left cluster contains a number of indices of location describing specific components of the flow regime often related to the central tendency of flow conditions. These indices include: mean and median daily flows (M_A1, M_A2); mean, minimum and maximum monthly flows (M_A12–23, M_L1–12, M_H1–12); magnitude of low-flow conditions (M_L15–17, 19–20, 22), duration of minima and maxima flow conditions (D_L1–5, D_H1–5) and predictability of average and low flows (T_A2, T_L3–4).

In contrast, the upper right cluster contains mainly indices of dispersion, describing the variability component of the flow regime. These dispersion-based indices include: variability in the magnitude of daily flows (M_A3, 5), monthly flows (M_A24–35), annual flows (M_A42–44, 45), and low flow conditions (M_L13, 18, 21); variability in the frequency of low and high flow conditions (F_L2, F_H2); variability in the duration of low and high flow conditions (D_L6–10, 17, D_H6–10, 16); and variability in the rate of change in flow conditions (R_A2, 9). The upper right cluster also contains a number of location-based indices describing the magnitude (M_H18, 21–27), frequency (F_H3–4) and duration (D_H11–13, 16–21) of high flow conditions.

Additional, smaller groups of inter-correlated indices are also present in Figure 2, including: ranges or spreads in daily flows (M_A6–11) and flood frequency (F_H5–6, 8–9), as well as indices that are calculated using the same equation but whose values differ due to different numeric thresholds for defining the particular flow event, e.g. variability across annual flows (M_A42–44), high flow discharge (M_H15–17), high peak flow (M_H24–27), flood frequency (F_H5–6, 8–9), low exceedence flows (D_L14–15), and high flow duration (D_H17–21). Finally, indices located close to the origin of Figure 2 represent hydrologic indicators that are generally uncorrelated with the majority of the other indicators that have higher loadings on the first two principal components; these include a number of indices describing the timing of flow events.

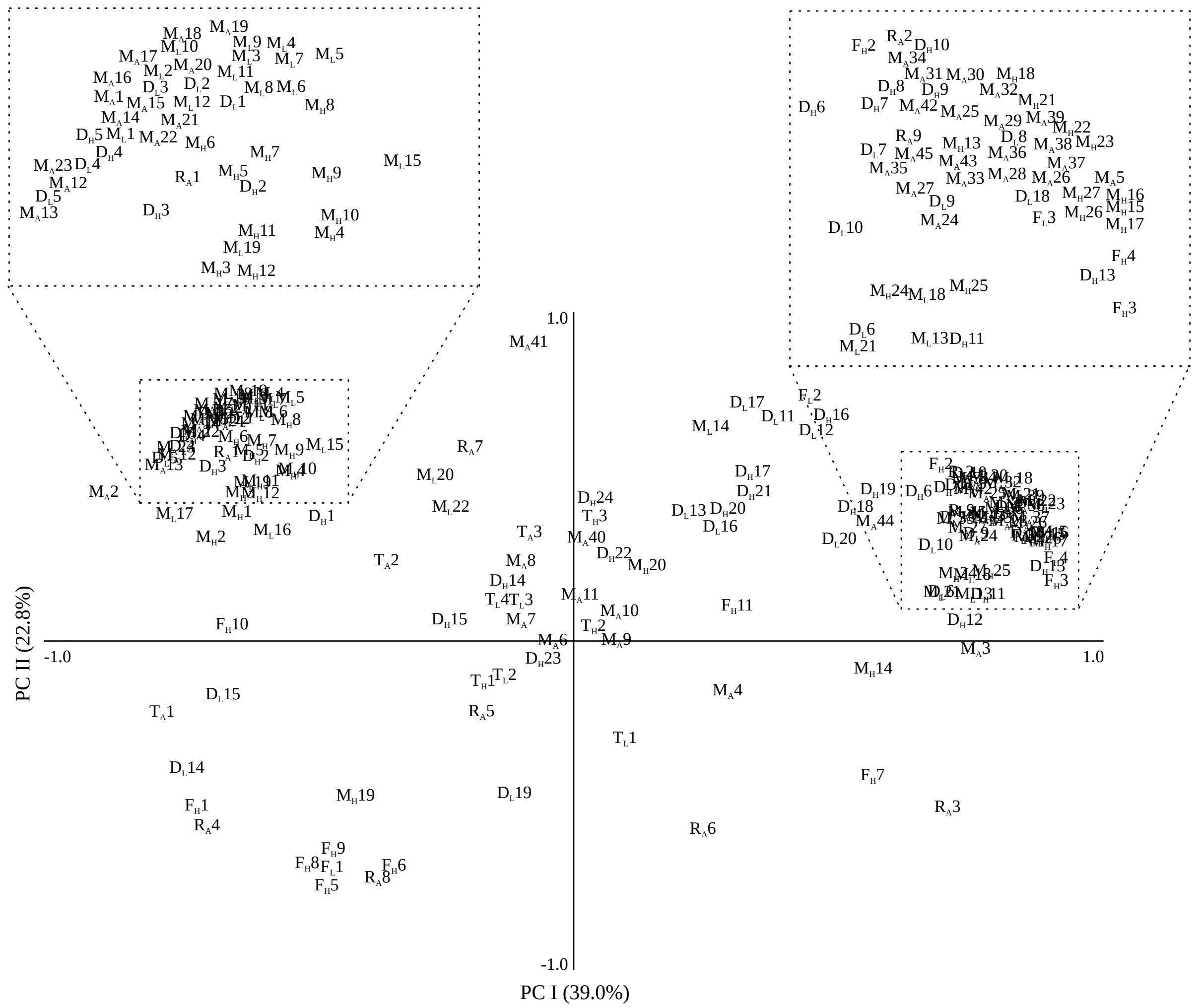

Figure 2. Ordination from the principal component analysis of the 420 stream sites based on 171 hydrologic indices. Correlations between indices are interpreted as the cosine of the angle between their index-axes (i.e. between the vectors joining the origin and the index positions in Euclidean space), and not the proximity between the apices of their axes (i.e. the distance between the index locations in Euclidean space). Note that each eigenvector k was rescaled to length $\sqrt{\lambda_k}$ (i.e. square-root of the kth eigenvalue) in order to accurately display the correlations among indices in ordination space. Some of the data points were jittered (i.e. a random error was added) to improve clarity

Selection of high information, non-redundant hydrologic indices

The first analysis identified groups of indices that exhibit the largest absolute loadings on each significant principal-component axis for all streams and the six stream types. These groups represent the indices that account for the majority of the variation provided by all the indices and subsets of indices that are relatively independent from each other. The significance of the index loadings cannot be tested using a standard statistical test (e.g. Pearson correlation coefficient) because the principal components are linear combinations of the indices themselves and thus are inherently correlated (Legendre and Legendre, 1998); therefore, we decided to select at least 25 indices with the highest absolute loadings on the significant principal-component axes for each stream type in order to provide a list of reasonable length for researchers to draw from. In order to accurately represent the relative importance of the principal-component axes, the number of indices listed for each component was set equal to the proportion of variation explained by the component compared to all significant axes. For example, based on all streams the first principal component explained 39.1% of the total 75.7% of the variance explained by the four significant principal components resulting in 13 out of the 25 indices being listed under PC I. The one exception to this rule was that a minimum of three indices for each significant component was reported. Table II presents the results from this analysis, highlighting the groups of indices that are representative of the major gradients of variation described by the entire index population. Hydrologic indices representing all nine components of the flow regime are contained in Table II, and a number of indices consistently explain dominant gradient of variation across the stream types (see the section 'Transferability of hydrologic indices').

Next, we were interested in selecting high information, non-redundant hydrologic indices, with the constraint that indices would represent each of the nine main components of the flow regime (Table III). By selecting the index with the highest absolute loading for each of the two to four significant principal-component axes for each category of streamflow characteristics, we present a list of two to four indices that represent the particular facet of the flow regime and that are relatively independent of each other (because they are derived from different principal-component axes). Dominant indices range from being specific to a single stream type (e.g. M_A3 for superstable/stable groundwater, D_L5 for snowmelt) to being shared among groups of stream types (e.g. M_L15 and D_L1 for intermittent streams) to illustrating wider affinities across stream types (e.g. T_A1 and R_A9).

Indicators of Hydrologic Alteration

Figure 3 illustrates the correlation plot from the PCA on all 171 indices but plotting only the positions of the IHAs. It is evident that the IHAs adequately represent the entire ordination space occupied by the 171 hydrologic indices and thus capture the majority of the information provided by the population of indices available to researchers. A number of the IHAs exhibit a high degree of inter-correlation (e.g. mean monthly flows, M_A12–23; variability in monthly flows, M_A24–35) and also contribute highly to the principal-component axes. Table II illustrates that IHAs are contained in almost all lists of the dominant indices for the significant principal-component axes (17 out of the 21 lists). One notable absence is the dominant indices for PC I based on all streams combined, where no IHAs were reported. However, it is important to mention that only the top 13 indices were reported and that the next two indices exhibiting the highest absolute loadings (i.e. the 14th and 15th largest loadings) for that principal component are IHAs (D_L18 and M_A26). Similarly, IHAs represent the majority of the nine major flow components for all of the stream types (Table III), although none are reported for the magnitude of high flow events because we did not classify any IHAs into this category (see Appendix). Given the results above, a number of IHAs can be selected from Table III that represent the major aspects of the flow regime while minimizing index redundancy in subsequent analyses.

Transferability of hydrologic indices

The results from the Mantel test (Table IV) show that the hydrologic indices exhibit varying degrees of similarity in their patterns of inter-correlation across the six stream types and all streams combined, and therefore exhibit varying degrees of transferability. The Mantel r statistic was positive for all comparisons, indicating that patterns of redundancy within streams types were relatively similar across stream types. Correlation matrices were very similar ($r > 0.74$) for the groups of perennial streams (i.e. snowmelt, snow and rain, superstable/stable groundwater, and perennial flashy/runoff streams), suggesting that hydrologic indices are somewhat transferable among perennial streams. By contrast, intermittent streams (i.e. harsh and flashy/runoff) exhibited lower correlations with other stream types, and with each other, suggesting a lack of transferability of hydrologic indices among intermittent streams. Within the intermittent stream types, harsh intermittent streams were most similar to intermittent and perennial flashy/runoff streams ($r > 0.50$) and differed substantially from snowmelt streams ($r = 0.27$). By contrast, intermittent flashy/runoff were less similar to harsh intermittent ($r = 0.54$) compared to other perennial stream types ($r > 0.56$). Among perennial streams, there was a surprisingly strong relationship between perennial flashy/runoff and superstable/stable groundwater streams ($r = 0.91$). Finally, the index correlation matrix for all streams combined exhibited the

Table II. Hydrologic indices (placed in descending order from top to bottom) exhibiting the largest absolute loadings on each statistically significant principal component

	Stream classification						All streams
	Intermittent		Perennial				
	Harsh intermittent	Intermittent flashy or runoff	Snowmelt	Snow and rain	Superstable or stable groundwater	Perennial flashy or runoff	
PC I							
	$M_{A}34$	**$D_{L}18$**	**$M_{A}29^{-}$**	$M_{L}13$	$F_{H}3$	$D_{H}13$	$F_{H}3$
	$M_{A}5$	$M_{H}23$	$D_{H}19^{-}$	$D_{H}12$	$F_{H}4$	**$D_{L}9$**	$F_{H}4$
	$M_{A}41$	$M_{A}37$	$D_{H}20^{-}$	$D_{H}11$	$T_{A}1^{-}$	**$M_{A}26$**	$M_{A}5$
	$M_{H}23$	$M_{A}38$	**$M_{A}12$**	$F_{H}3$	$M_{A}3$	$M_{A}38$	$M_{H}16$
	$M_{H}22$	**$R_{A}9$**	**$M_{A}13$**	$M_{L}21$	$F_{L}3$	$M_{A}37$	$M_{H}17$
	$M_{A}30$	**$D_{L}8$**	**$M_{A}14$**	**$D_{L}6$**	**$D_{L}9$**	$M_{H}23$	$D_{H}13$
	$M_{A}39$	**$M_{A}33$**	**$M_{A}23$**	$F_{H}4$	$M_{H}17$	$M_{H}15$	$M_{H}15$
	$D_{H}10$	**$D_{L}10$**	$F_{H}8$	$T_{A}1^{-}$	$D_{H}11$	$M_{H}26$	$M_{H}23$
	$M_{A}25$	$D_{L}14^{-}$	**$D_{L}5$**	**$M_{L}18$**	**$D_{L}10$**	$M_{A}5$	$M_{H}26$
	$M_{H}16$	$F_{H}3$	$D_{H}13^{-}$	$D_{H}13$	$M_{H}25$	**$M_{A}28$**	$M_{H}22$
	$R_{A}4^{-}$	$M_{A}39$	$D_{H}18^{-}$	$M_{H}17$	$M_{H}15$	$F_{H}4$	$M_{A}2^{-}$
	$M_{A}35$	**$M_{A}24$**	$M_{A}1$	$M_{H}25$	$M_{H}16$	**$D_{L}10$**	$M_{H}27$
	$M_{A}38$	$D_{L}15^{-}$	$M_{A}2$	**$D_{L}18$**	$M_{H}24$	$M_{H}22$	$M_{A}37$
	$M_{A}33$		$M_{H}1$	$M_{H}26$	$M_{H}27$	$M_{A}39$	
	$M_{A}45$		$M_{H}2$	$F_{L}3$	$M_{A}5$	$M_{A}36$	
	$M_{L}13$		**$R_{A}1$**	$M_{H}1^{-}$	$M_{H}26$	$M_{H}16$	
	$M_{H}15$		**$R_{A}3^{-}$**	$M_{H}2^{-}$	**$M_{L}18$**	$F_{H}3$	
			$D_{L}1$	$D_{L}15^{-}$		$M_{A}2^{-}$	
			$D_{L}2$	$M_{H}16$			
			$M_{L}13^{-}$	$M_{H}27$			
			$M_{L}19$	$M_{A}5$			
			$M_{H}23^{-}$	**$D_{L}8$**			
			$D_{H}4$				
			$D_{H}5$				
PC II							
	$M_{H}14$	$F_{H}7^{-}$	$M_{L}22$	$M_{L}14^{-}$	$F_{H}6$	$M_{A}41$	$M_{A}41$
	$M_{H}11$	$M_{L}6$	**$D_{L}16^{-}$**	**$R_{A}8$**	$F_{H}8$	**$D_{L}17$**	**$M_{A}19$**
	$D_{H}5$	$M_{L}7$	$M_{A}40$	$D_{L}13^{-}$	$D_{H}20^{-}$	$M_{L}14$	$M_{L}4$
	$M_{A}22$	$M_{L}5$			$F_{H}5$	$M_{L}22$	**$M_{A}18$**
	$D_{L}1$	**$D_{H}15$**			$D_{H}17^{-}$		$M_{L}9$
		$M_{A}18$			$D_{L}11^{-}$		$M_{L}5$
					$M_{L}14^{-}$		$F_{H}6^{-}$
PC III							
	$R_{A}5^{-}$	$M_{L}22^{-}$			$R_{A}5$	$R_{A}6^{-}$	$R_{A}6^{-}$
	$M_{L}1^{-}$	$M_{L}11^{-}$			**$T_{L}2$**	$D_{H}24^{-}$	$F_{H}7^{-}$
	$M_{L}20^{-}$	**$M_{A}21^{-}$**			$M_{H}10$	$T_{H}3^{-}$	**$D_{L}16$**
		$D_{L}13^{-}$					
PC IV							
		$D_{H}23$					$D_{L}13^{-}$
		$M_{H}7^{-}$					**$D_{H}15$**
		$M_{L}15^{-}$					**$T_{L}2^{-}$**

Note that the superscript minus sign indicates a negative loading of the index on the principal component (although the direction of the loading is not important for selecting non-redundant indices); bold indices represent Indicators of Hydrologic Alteration.

Table III. Hydrologic indices with the largest absolute loading for each of the two to four statistical significant principal components for each stream type in each of the nine components of the flow regime

Flow component	Stream classification						All streams
	Intermittent		Perennial				
	Harsh intermittent	Intermittent flashy or runoff	Snowmelt	Snow and rain	Superstable or stable groundwater	Perennial flashy or runoff	
Magnitude of flow events							
Average flow conditions	$\mathbf{M_A34}$, $\mathbf{M_A22}$, $\mathbf{M_A16}$	M_A37, $\mathbf{M_A18}$, $\mathbf{M_A21}$, M_A9	$\mathbf{M_A29}$, M_A40	M_A3, M_A44	M_A3, M_A41, M_A8	$\mathbf{M_A26}$, M_A41, M_A10	M_A5, M_A41, M_A3, M_A11
Low flow conditions	M_L13, M_L15, M_L1	M_L16, M_L6, M_L22, M_L15	M_L13, M_L22	M_L13, M_L14	$\mathbf{M_L18}$, M_L14, M_L16	$\mathbf{M_L17}$, M_L14, M_L16	$\mathbf{M_L17}$, M_L4, M_L21, M_L18
High flow conditions	M_H23, M_H14, M_H9	M_H23, M_H4, M_H14, M_H7	M_H1, M_H20	M_H17, M_H20	M_H17, M_H19, M_H10	M_H23, M_H8, M_H14	M_H16, M_H8, M_H10, M_H14
Frequency of flow events							
Low flow conditions	$\mathbf{F_L2}$, F_L3, $\mathbf{F_L1}$	F_L3, $\mathbf{F_L2}$, $\mathbf{F_L1}$	F_L3, $\mathbf{F_L2}$	F_L3, $\mathbf{F_L2}$	F_L3, $\mathbf{F_L1}$, $\mathbf{F_L2}$	F_L3, $\mathbf{F_L2}$, F_L3	F_L3, $\mathbf{F_L2}$, F_L3, $\mathbf{F_L1}$
High flow conditions	$\mathbf{F_H2}$, F_H5, F_H7	F_H3, F_H7, $\mathbf{F_H2}$, F_H10	F_H8, F_H11	F_H3, F_H5	F_H3, F_H6, F_H11	F_H4, F_H6, F_H7	F_H3, F_H6, F_H7, $\mathbf{F_H2}$
Duration of flow events							
Low flow conditions	D_L13, $\mathbf{D_L1}$, $\mathbf{D_L2}$	$\mathbf{D_L18}$, $\mathbf{D_L16}$, D_L13, $\mathbf{D_L1}$	$\mathbf{D_L5}$, $\mathbf{D_L16}$	$\mathbf{D_L6}$, D_L13	$\mathbf{D_L9}$, D_L11, $\mathbf{D_L16}$	$\mathbf{D_L10}$, $\mathbf{D_L17}$, $\mathbf{D_L6}$	$\mathbf{D_L18}$, $\mathbf{D_L17}$, $\mathbf{D_L16}$, D_L13
High flow conditions	$\mathbf{D_H10}$, $\mathbf{D_H5}$, D_H22	D_H13, $\mathbf{D_H15}$, D_H12, D_H23	D_H19, $\mathbf{D_H16}$	D_H12, D_H24	D_H11, D_H20, $\mathbf{D_H15}$	D_H13, $\mathbf{D_H16}$, D_H24	D_H13, $\mathbf{D_H16}$, D_H20, $\mathbf{D_H15}$
Timing of flow events	$\mathbf{T_H1}$, $\mathbf{T_L2}$, $\mathbf{T_H2}$	T_A1, T_A2, $\mathbf{T_L1}$, T_H3	T_A1, T_A3	T_A1, $\mathbf{T_L1}$	T_A1, $\mathbf{T_H1}$, $\mathbf{T_L2}$	T_A1, T_A3, T_H3	T_A1, T_H3, T_A1, $\mathbf{T_L2}$
Rate of change in flow events	$\mathbf{R_A4}$, $\mathbf{R_A1}$, R_A5	$\mathbf{R_A9}$, R_A6, R_A5, R_A7	$\mathbf{R_A1}$, $\mathbf{R_A8}$	$\mathbf{R_A9}$, $\mathbf{R_A8}$	$\mathbf{R_A9}$, $\mathbf{R_A8}$, R_A5	$\mathbf{R_A9}$, R_A7, R_A6	$\mathbf{R_A9}$, $\mathbf{R_A8}$, R_A6, R_A5

For example, based on all 420 streams the hydrologic indices M_A5, M_A41, M_A3, M_A11 exhibit the largest absolute loadings on first, second, third and fourth principal components, respectively, for the magnitude of average flow conditions. Bold indices represent Indicators of Hydrologic Alteration.

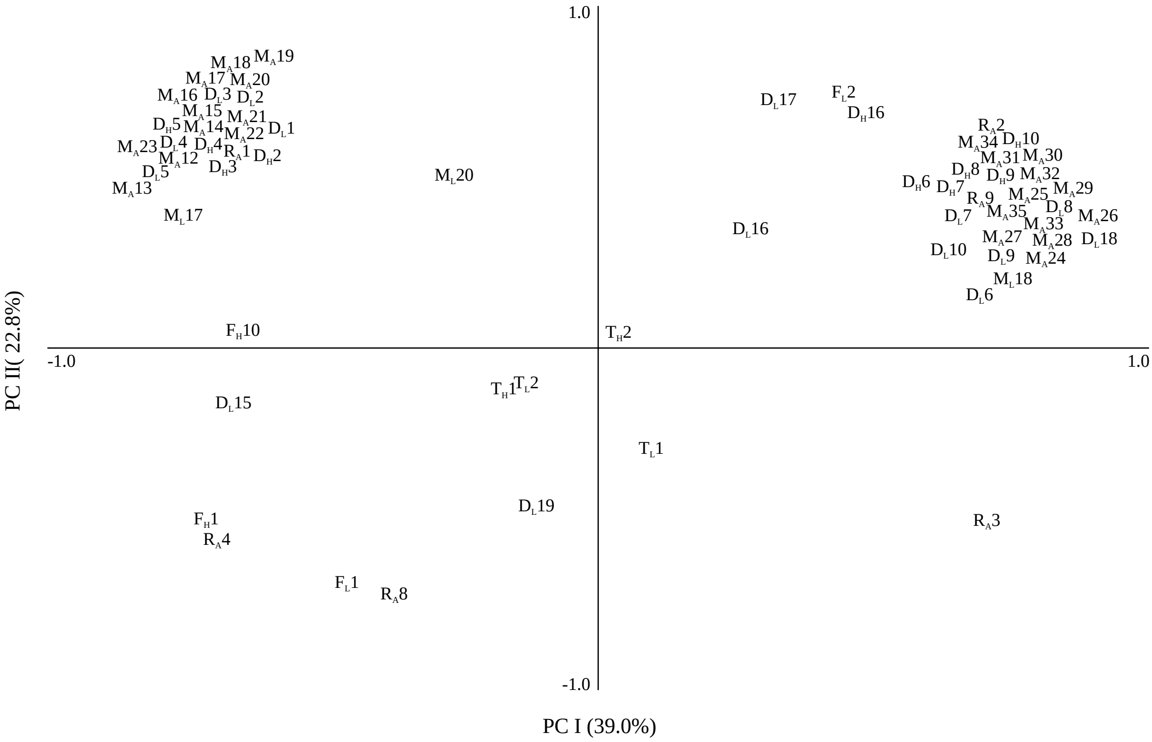

Figure 3. Ordination from the principal component analysis of the 420 stream sites based on 171 hydrologic indices (see Figure 2) but plotting only the positions of the Indicators of Hydrologic Alteration (IHA). Note that the IHAs efficiently represent the entire ordination space occupied by the 171 hydrologic indices in Figure 2 and thus capture the majority of the information provided by the population of available indices. Some of the data points were jittered to improve clarity. See Figure 2 caption for the description of the interpretation of index intercorrelations

Table IV. Degree of concordance between the correlation matrices (i.e. pair-wise correlations between the 171 hydrologic indices) for each stream type measured as the Mantel r statistic

	Harsh intermittent	Intermittent flashy or runoff	Snowmelt	Snow and rain	Superstable or stable groundwater	Perennial flashy or runoff	All streams
Harsh intermittent	—						
Intermittent flashy or runoff	0.542	—					
Snowmelt	0.274	0.556	—				
Snow and rain	0.417	0.630	0.905	—			
Superstable or stable groundwater	0.488	0.694	0.742	0.860	—		
Perennial flashy or runoff	0.537	0.754	0.777	0.861	0.912	—	
All streams	0.492	0.771	0.815	0.913	0.939	0.965	—

strongest relationships with all six stream types. This result is not surprising, given that observations in each stream type are contained in the all-streams group.

Comparing the dominant, reoccurring indices in Table II, we see a number of similarities across stream types. For example, M_A5, M_H16, F_H3 appear consistently in the PC I list, indicating that these indices explain a substantial proportion of the variation in all the indices, regardless of the stream type. Similarly, a number of stream types share the importance of particular hydrologic indices, including intermittent streams (M_A33, 38, 39, M_H23), perennial streams (M_A5, M_L14, M_H16, 26, F_H3, 4), flashy or runoff streams (M_A37–39, D_L10, F_H3), and snowmelt and snow and rain streams (M_L13, D_H13). In general, snowmelt streams share little in common with the other stream types. In summary, similarities in the dominant hydrologic indices among stream types indicate the potential universality of selected indices for future studies, although the number of indices not shared among stream types was greater.

DISCUSSION

In recent years the development and application of indices describing hydrological conditions of streams and rivers has exploded in the literature, resulting in a dramatic shift from a paucity of indices in the past to the plethora of indices now available. Consequently, researchers are now confronted with the task of having to choose among a large number of competing hydrologic indices in order to reduce computational effort and index redundancy prior to statistical analyses. Given the potential ecological implications of the information provided by hydrologic indices (e.g. Poff and Ward, 1989; Richter *et al*., 1996, 1997, 1998; Poff *et al*., 1997; Puckridge *et al*., 1998; Clausen and Biggs, 2000), it is desirable that indices describing unique or non-redundant patterns of variance (in relation to the other indices) are selected and subsequently used in hydro ecological studies. Failure to remove index redundancy prior to analyses will result in a number of statistical problems, including the deleterious effects of multicollinearity (e.g. biased and imprecise estimates of the regression coefficients: Zar, 1999), biased model selection (e.g. erroneous selection of random variables in the regression model when examining large numbers of variables: Olden and Jackson, 2000) and the interaction between the two (e.g. failure to identify significant variables: Routledge, 1990). In addition, the ability to reduce the population of indices to a smaller, manageable subset has a number of logistical benefits, including reduced time and resources expended.

The present paper provides the first comprehensive examination of the degree of intercorrelation among existing hydrologic indices in the literature (but see Poff (1996) and Clausen and Biggs (2000) for analyses based on many fewer indices). The results from this examination offer a number of statistical- and ecological-based recommendations for how many, and which, indices should be employed in future hydroecological studies. In addition, these analyses can offer either general recommendations for characterizing streams exhibiting a diverse range of hydrologic conditions (optimal for regional- or continental-scale analyses) or specific recommendations for streams exhibiting hydrologic characteristics that are highly constrained by regional climatic and geological features (optimal for local- or regional-scale analyses). Together, the results provide researchers and managers with detailed guidance for selecting high information, non-redundant indices that represent the major facets of the flow regime.

In a purely statistical sense, we show how the total number of indices can be reduced from the original 171 to between two and four indices (i.e. first index for each principal-component axis in Table II) that describe the dominant patterns of hydrologic variability. Such an approach may be particularly useful in large-scale, data-intensive studies where indices other than hydrologic indices are being examined and related to patterns in biological data. Furthermore, although this approach does not account for the particular component of the flow regime that the index was developed to describe, Table II still provides the researcher with a degree of flexibility regarding the choice of indices representing each of the dominant gradients (i.e. principal-component axes). Therefore, indices describing aspects of the flow regime that closely relate to the ecological question of interest can be selected. Similarly, one could reduce the population of indices to a minimum of nine, each of which exhibits the highest absolute loading for the first principal-component axes for each of the nine distinct components of the flow regime (Table III). This ensures that the majority of the variation is accounted for and that different facets of the flow regimes are adequately represented in subsequent analyses. Furthermore, given the particular ecological question being addressed, additional indices within each flow component could be selected (from the remaining significant principal components), which would not result in a substantial increase in redundancy (although some redundancy among indices representing different flow components may exist: see Table II). Given the importance of the full spectrum of hydrologic conditions that shape the distribution of riverine flora and fauna (Sparks *et al*., 1990; Schlosser, 1991; Stanford *et al*., 1996; Poff *et al*., 1997), this approach may be especially favourable since it maximizes the information provided by the indices while minimizing the degree of redundancy.

The results from this study provide a framework from which high information, non-redundant hydrological indices describing different aspects of the flow regime can be selected to best match the particular ecological question of interest. Here we highlight the ecological importance of a number of hydrologic indices found to represent dominant patterns of variation for particular stream types and for all streams combined. Skewness in daily flows (M_A5) was found to be one of the most consistently dominant indices across all stream types and may be a particularly important measure of daily flow conditions for certain riverine taxa, e.g. examining the response of fish assemblages to erratic water releases below hydroelectric dams (e.g. Kinsolving and Bain, 1993). Interannual variation in daily discharge in months preceding breeding seasons may also be important for both final maturation and spawning of species (e.g. Jackson, 1989) and on post-spawning recruitment (e.g. Humphries and Lake, 2000). Researchers studying the seasonal dynamics of lotic plant communities in intermittent or perennial flashy/runoff streams may select a measure of monthly variability in discharge (one of M_A36–39) in order to account for the majority of variation in the indices and to account for the ecological importance of low and high monthly flow events in dictating reproduction, arrival of propagules and density of plant cover (Hughes, 1990). In snowmelt- and snow/rain-driven streams (i.e. in high elevation montane environments or high latitudes), the selection of indices describing the magnitude of average (M_A12, 13) and maximum (M_H1, 2) October and November flows may be particularly important when studying the population dynamics of native and non-native stream fishes. Brown trout (*Salmo trutta*) and brook trout (*Salvelinus fontinalis*) often spawn during these months, and therefore indices describing this aspect of the hydrograph may be especially beneficial given their negative interactions with native cutthroat trout (*Salmo clarki*). For example, Strange *et al*. (1992) conducted a simulation experiment and found that pre-recruitment discharges (corresponding to the months prior to December) significantly affected relative abundances of brown trout and brook trout, and caused shifts in the structure of the fish communities.

Hydrologic indices representing the duration of floods in snowmelt-driven streams (one of D_H4, 5, 13, 18–20) are particularly important given the importance of flood events in maintaining riparian diversity through their influence on sediment dynamics (Molles *et al*., 1998). Hydrologic indices describing monthly (30 days) and seasonal (90 days) duration of high flows (i.e. D_H4, D_H5, D_H13) are especially good candidates for riparian studies since model predictions suggest that annual flood duration may be critical in determining the ability of riparian forest patch types to persist within their natural range of abundance (Richter and Richter, 2000). Similarly, selecting indices describing high peak flows (i.e. M_H25 or M_H26) in snow/rain stream types may be attractive since these flow conditions directly influence cottonwood (*Populus* spp.) recruitment (Scott *et al*., 1997). A measure of high flood pulses (i.e. F_H2, 3) and the rate of change in flow conditions (i.e. R_A9) for flashy intermittent streams may be a good choice of index when studying native and non-native persistence and coexistence (e.g. Minckley and Deacon, 1991). In a dramatic example, Meffe (1984) documented that a native fish, the Gila topminnow (*Poeciliopsis occidentalis*), was locally extirpated by the introduced predatory mosquitofish (*Gambusia affinis*) in locations where natural flash floods were regulated by upstream dams, but native species persisted in naturally flashy streams. Indices describing the timing, or predictability of flow events (i.e. T_A1) may be important for perennial snow/rain and superstable/stable groundwater streams given their high information, non-redundant nature and the importance of such conditions during critical life history stages of riverine fauna. For example, Fausch *et al*. (2001) found that rainbow trout invasion success was best explained by the temporal concordance between timing of fry emergence and the timing of months with low flood probability. In addition, quantifying the timing of floods (T_A1, 3) would be important given that there may be a selective advantage of linking reproductive output to flood magnitude. For example, Puckridge *et al*. (2000) suggest that producing a proportionate number of offspring would enable fish species to readily colonize new habitats during floods, and reach new refugia before the next drought. Consequently, although timing of flow indices are under-represented in Table II, it is essential that such indices are included in hydroecological studies given their critical ecological importance (see discussion below).

Researchers have used a number of criteria when deciding which and how many hydrologic indices are used in a study, ranging from objective selection to personal preference to ease in computation. Indeed, the major stumbling block in this process involves the calculation of the indices since this requires user-written computer macros. Consequently, relatively simple measures of streamflow conditions (e.g. mean, median, maximum, minimum flows) are often used in hydroecological studies. For this reason, recent attention has focused on the Indicators of Hydrologic Alteration (IHA) method (Richter *et al.*, 1996) since this approach is accompanied with Windows-based computer software that calculates a multiparameter suite of hydrologic indices. The results from our study show that the IHA method adequately represents the majority of the variation explained by the entire population of 171 indices and thus captures the majority of the information available. Furthermore, the IHAs represent almost all of the major components of the flow regime, and therefore provide a good balance between objective selection of high information indices and accessibility in terms of computation. However, it is important to note two solvable shortcomings of the IHAs revealed in this analysis. First, based on our classification of the indices, no IHAs directly quantify the magnitude of high flow conditions, and therefore are not represented in Table III. However, the measures M_H14, M_H17, M_H20 and M_H23 are highly represented and therefore may be suitable indices to supplement the IHAs (especially M_H14 or M_H20 since these are easily calculated). Second, no IHAs were found to exhibit high loadings on the first principal-component axis based on all streams combined, although only the top 13 loading indices were reported (Table II). However, if this list were lengthened, two IHAs would represent the 14th and 15th largest loadings for the first principal component (D_L18 and M_A26). Furthermore, one could use another index in that list (e.g. F_H3, F_H4, M_A5) to represent the dominant gradient of variation given that the formulation of F_H3 and F_H4 are identical to F_H1 (an IHA index) but are based on different threshold criteria for defining a high flood pulse (note: IHA also allows the user to define high pulse threshold). In summary, the Indicators of Hydrologic Alteration can provide a powerful tool for the calculation of high information, non-redundant indices describing the major components of the flow regime; however, like the case with all the indices, only a subset of the IHAs should be used in any analyses.

An important question that requires additional research is whether hydrologic indices can be geographically transferred between regions of differing climatic and geologic settings, both continentally and globally. We statistically assessed this question by looking at different stream types (Poff, 1996) as defined by classification on a subset of the hydrologic indices analysed here (ten indices) and examined whether particular indices consistently explained dominant patterns of the variation. Although not globally exhaustive, many of the stream types examined in this study are representative of range of types that occur commonly throughout the world (i.e. snowmelt-dominated, groundwater-dominated and intermittent streams). We found that the degree of hydrologic index transferability among stream types varied greatly. Based on overall similarities among stream-type correlation matrices, transferability was highest among perennial streams, lowest among intermittent streams, and intermediate between perennial and intermittent flashy/runoff streams. The weak transferability between intermittent harsh and perennial snowmelt streams might be expected, yet the strong transferability between perennial flashy/runoff and superstable/stable groundwater was surprising. Examining patterns in individual indices revealed that although some indices were transferable between particular stream types (i.e. skewness in daily flows, high flow discharge, high flood pulse count), in general, indices explaining dominant patterns of variance were found to be stream-type specific. This finding was especially true when the components of the flow regime are accounted for. We suggest that although particular hydrologic indices may be statistically transferable among particular stream types, in general, the choice of hydrologic indices should reflect the specific hydroclimatic characteristics of the study region.

CONCLUSION

In the present study we have provided a statistically based framework to aid in the selection of hydrologic indices for future hydroecological studies. By focusing on inter-relationships among the hydrologic indices, one can select a subset of optimal indices based on the hydroclimatic region in which the study stream is located and the particular ecological question being addressed. This will maximize the information provided by the selected indices while minimizing the degree of redundancy in all subsequent analyses. It is important to note, however, that although we provide a quantitative basis for the selection of hydrologic indices, our approach should only be used as an aid in the selection of hydrologic indices. Wherever possible, it should be used in conjugation with more intuitive index selection criteria based on the particular ecological question of interest. For example, the fact that indices describing the timing of flow events did not explain dominant patterns of variation does not imply that such indices should not be used. Rather, this suggests that timing indices represent a portion of the total variation that is not represented by the other hydrologic indices. Given the importance of the timing of flows (see Poff *et al*., 1997), for example in synchronizing environmental cycles and the reproductive cycles of native fish (Gehrke *et al*., 1995), driving seasonal patterns in lotic plant communities (Hughes, 1990) and promoting riparian tree recruitment (Scott *et al*., 1997), it is obvious that such indices should be included in hydroecological studies. For this reason, we suggest that the results from our study be used to select high-information, non-redundant hydrologic indices that represent each of the major facets of the flow regime. Furthermore, although we have examined a total of 171 hydrologic indices derived from a number of published studies, additional indices may have to be developed to account for question-specific aspects of the hydrograph. In a good example, Galat and Lipkin (2000) used the IHA indices, but also included the Julian date of the vegetation 'growing season' one-day minimum flow, which are critical to many species of the Missouri River.

In conclusion, the results from this study provide statistically sound recommendations on which flow indices can be used to adequately characterize flow regimes in a non-redundant manner. In combination with ecological knowledge and investigator creativity, this can help guide researchers in the parsimonious selection of hydrologic indices for future hydroecological studies.

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APPENDIX

Description of the 171 hydrologic indices used in the study

Code	U	T	Hydrologic index	Definition	Reference[a]
Magnitude of flow events					
Average flow conditions					
M_A1	1	D	Mean daily flows	Mean daily flow	1,2,3
M_A2	1	D	Median daily flows	Median daily flow	1,2,3
M_A3	6	D	Variability in daily flows 1	Coefficient of variation in daily flows	1,2,3,5,6
M_A4	6	D	Variability in daily flows 2	Coefficient of variation of the logs in daily flows corresponding to the {5^{th}, 10^{th}, 15^{th}, ..., 85^{th}, 90^{th} 95^{th}} percentiles	8
M_A5	6	D	Skewness in daily flows	Mean daily flows divided by median daily flows	1,2,3
$M_A6–8$	6	D	Ranges in daily flows	Ratio of $10^{th}/90^{th}$, $20^{th}/80^{th}$ and $25^{th}/75^{th}$ percentiles in daily flows over all years	8
$M_A9–11$	2	D	Spreads in daily flows	Ranges in daily flows ($M_A6–8$) divided by median daily flows	8
$M_A12–23$	1	M	Mean monthly flows	Mean monthly flow for all months	3,9,10,11,12
$M_A24–35$	6	M	Variability in monthly flows	Coefficient of variation in monthly flows for all months	3,9,10,11
$M_A36–38$	6	M	Variability across monthly flows 1	Variability in monthly flows divided by median monthly flows, where variability is calculated as range, interquartile, and $90^{th}–10^{th}$ percentile.	7
M_A39	6	M	Variability across monthly flows 2	Coefficient of variation in mean monthly flows	4
M_A40	6	M	Skewness in monthly flows	(Mean monthly flow—median monthly flow)/median monthly flow	7
M_A41	3	A	Mean annual runoff	Mean annual flow divided by catchment area	4
$M_A42–44$	6	A	Variability across annual flows	Variability in annual flows divided by median annual flows, where variability is calculated as range, interquartile, and $90^{th}–10^{th}$ percentile.	7
M_A45	6	A	Skewness in annual flows	(Mean annual flow—median annual flow)/median annual flow	7
Low flow conditions					
$M_L1–12$	1	M	Mean minimum monthly flows	Mean minimum monthly flow for all months	12
M_L13	6	M	Variability across minimum monthly flows	Coefficient of variation in minimum monthly flows	4
M_L14	6	A	Mean of annual minimum flows	Mean of the lowest annual daily flow divided by median annual daily flow averaged across all years	12
M_L15	6	A	Low flow index	Mean of the lowest annual daily flow divided by mean annual daily flow averaged across all years	5
M_L16	6	A	Median of annual minimum flows 2	Median of the lowest annual daily flows divided by median annual daily flows averaged across all years	3

(*continued overleaf*)

Appendix (Continued)

Code	U	T	Hydrologic index	Definition	Reference[a]
M_L17	6	A	Baseflow index 1	Seven-day minimum flow divided by mean annual daily flows averaged across all years	11
M_L18	6	A	Variability in Baseflow Index 1	Coefficient of variation in M_L17	11
M_L19	6	A	Baseflow index 2	Mean of the ratio of the lowest annual daily flow to the mean annual daily flow times 100 averaged across all years	6
M_L20	6	A	Baseflow index 3	Ratio of baseflow volume to total flow volume	1,2,3
M_L21	6	A	Variability across annual minimum flows	Coefficient of variation in annual minimum flows averaged across all years	4
M_L22	3	A	Specific mean annual minimum flows	Mean annual minimum flows divided by catchment area	4
High flow conditions					
M_H1–12	1	M	Mean maximum monthly flows	Mean of the maximum monthly flows for all months	12
M_H13	6	M	Variability across maximum monthly flows	Coefficient of variation in mean maximum monthly flows	4
M_H14	6	A	Median of annual maximum flows	Median of the highest annual daily flow divided by the median annual daily flow averaged across all years	3
M_H15–17	6	A	High flow discharge	Mean of the 1st, 10th and 25th percentile from the flow duration curve divided by median daily flow across all years	3
M_H18	6	A	Variability across annual maximum flows	Coefficient of variation of logarithmic annual maximum flows	4
M_H19	6	A	Skewness in annual maximum flows	See Hughes and James (1989)	4
M_H20	3	A	Specific mean annual maximum flows	Mean annual maximum flows divided by catchment area	4
M_H21–23	4	A	High flow volume	Mean of the high flow volume (calculated as the area between the hydrograph and the upper threshold during the high flow event) divided by median annual daily flow across all years. The upper threshold is defined as 1, 3, and 7 times median annual flow	1,2
M_H24–26	6	A	High peak flow 1	Mean of the high peak flow during the high flow event (defined by the upper threshold) divided by median annual daily flow. The upper threshold is defined as 1, 3, and 7 times median annual flow	1,2,3
M_H27	6	A	High peak flow 2	See M_H24–26, where the upper threshold is defined as the 25th percentile from the flow duration curve	3
Frequency of flow events					
Low flow conditions					
F_L1	5	A	Low flood pulse count	Number of annual occurrences during which the magnitude of flow remains below a lower threshold. Hydrologic pulses are defined as those periods within a year in which the flow drops below the 25th percentile (low pulse) of all daily values for the time period	9,10,11

F_L2	6	A	Variability in low flood pulse count	Coefficient of variation in F_L1	9,10,11
F_L3	5	A	Frequency of low flow spells	Total number of low flow spells (threshold equal to 5% of mean daily flow) divided by the record length in years	4
High flow conditions					
F_H1	5	A	High flood pulse count 1	See F_L1, where the high pulse is defined as the 75^{th} percentile	9,10,11
F_H2	6	A	Variability in high flood pulse count 1	Coefficient of variation in F_H1	9,10,11
$F_H3–4$	5	A	High flood pulse count 2	See F_H1, where the upper threshold is defined as 3 and 7 times median daily flow, and the value is represented as an average instead of a tabulated count	1,2
$F_H5–7$	5	A	Flood frequency 1	Mean number of high flow events per year using an upper threshold of 1, 3, and 7 times median flow over all years	1,2,3
$F_H8–9$	5	A	Flood frequency 2	See $F_H5–7$, where the 25^{th} and 75^{th} percentile are used as the upper threshold	3
F_H10	5	A	Flood frequency 3	See $F_H5–7$, where the median of the annual minima is used as the upper threshold	3
F_H11	5	A	Flood frequency 4	Mean number of discrete flood events per year	5,6
Duration of flow events					
Low flow conditions					
$D_L1–5$	1	D M A	Annual minima of 1-/3-/7-/30-/90-day means of daily discharge	Magnitude of minimum annual flow of various duration, ranging from daily to seasonal	9,10,11
$D_L6–10$	6	D M A	Variability in annual minima of one-/3-/7-/30-/90-day means of daily discharge	Coefficient of variation in $D_L1–5$	9,10,11
$D_L11–13$	6	D M	Means of 1-/7-/30-day minima of daily discharge	Mean annual 1-day/7-day/30-day minimum, respectively, divided by median flow	3
$D_L14–15$	1	A	Low exceedence flows	Mean magnitude of flows exceeded 75% and 90% of the time (calculated from the flow duration curve) divided by median daily flow, respectively, over all years	1,2,3
D_L16	4	A	Low flow pulse duration	Mean duration of F_L1	9,10,11
D_L17	6	A	Variability in low flow pulse duration	Coefficient of variation in D_L16	9,10,11
D_L18	5	A	Number of zero-flow days	Mean annual number of days having zero daily flow	5,6,11
D_L19	6	A	Variability in number of zero-flow days	Coefficient of variation in D_L18	11
D_L20	6	A	Percent of zero-flow months	Percentage of all months with zero flow	7
High flow conditions					
$D_H1–5$	1	D M A	Annual maxima of 1-/3-/7-/30-/90-day means of daily discharge	Magnitude of maximum annual flow of various duration, ranging from daily to seasonal	9,10,11

(*continued overleaf*)

Appendix (Continued)

Code	U	T	Hydrologic index	Definition	Reference[a]
D_H6–10	6	D M A	Variability in annual maxima of 1-/3-/7-/30-/90-day means of daily discharge	Coefficient of variation in D_H1–5	9,10,11
D_H11–13	6	D M	Means of 1-/7-/30-day maxima of daily discharge	Mean annual 1-day/7-day/30-day maximum, respectively, divided by median flow	3
D_H14	6	M	Flood duration 1	Monthly flow equalled or exceeded 95% of the time divided by mean monthly flow	4
D_H15	4	A	High flow pulse duration	Mean duration of F_H1	9,10,11
D_H16	6	A	Variability in high flow pulse duration	Coefficient of variation in D_H15	9,10,11
D_H17–19	4	A	High flow duration 1	See D_H15, where the upper threshold is defined as 1, 3, and 7 times median flows, and the value is represented as an average instead of a tabulated count	1,2,3
D_H20–21	4	A	High flow duration 2	See D_H17–19, where the upper threshold is defined as the 25th and 75th percentile of median flows	3
D_H22	4	A	Flood interval	Mean annual median interval in days between floods over all years	5
D_H23	4	A	Flood duration 2	Mean annual number of days that flows remain above the flood threshold averaged across all years	5,6
D_H24	4	A	Flood free days	Mean annual maximum number of 365 days over all water years during which no floods occurred over all years	5,6
Timing of flow events					
Average flow conditions					
T_A1	6	D	Constancy	See Colwell (1974)	1,2,3,5,6
T_A2	6	D	Predictability of flow	Composed of two independent, additive components: constancy (a measure of temporal invariance) and contingency (a measure of periodicity)	5,6
T_A3	6	M	Seasonal predictability of flooding	Maximum proportion of all floods over the period of record that fall in any one of six 60-day 'seasonal' windows	5,6
Low flow conditions					
T_L1	6	D	Julian date of annual minimum	The mean Julian date of the 1-day annual minimum flow over all years	3,9,10,11
T_L2	6	D	Variability in Julian date of annual minimum	Coefficient of variation in T_L1	3,9,10,11
T_L3	6	M	Seasonal predictability of low flow	Proportion of low-flow events $\geq$5-year magnitude falling in a 60-day 'seasonal' window	6

T_L4	6	M	Seasonal predictability of non-low flow	Maximum proportion of the year (number of days/365) during which no 5-year + low flows have ever occurred over the entire period of record	6
High flow conditions					
T_H1	6	D	Julian date of annual maximum	The mean Julian date of the 1-day annual maximum flow over all years	3,9,10,11
T_H2	6	D	Variability in Julian date of annual maximum	Coefficient of variation in T_H1	3,9,10,11
T_H3	6	M	Seasonal predictability of non-flooding	Maximum proportion of the year (number of days/365) during which no floods have ever occurred over the period of record	6
Rate of change in flow events					
Average flow conditions					
R_A1	7	D	Rise rate	Mean rate of positive changes in flow from one day to the next	9,10,11
R_A2	6	D	Variability in rise rate	Coefficient of variation in R_A1	9,10,11
R_A3	7	D	Fall rate	Mean rate of negative changes in flow from one day to the next	9,10,11
R_A4	6	D	Variability in fall rate	Coefficient of variation in R_A3	9,10,11
R_A5	6	D	No day rises	Ratio of days where the flow is higher than the previous day	3
$R_A6–7$	1	D	Change of flow	Median of difference between natural logarithm of flows between two consecutive days with increasing/decreasing flow	3
R_A8	5	D	Reversals	Number of negative and positive changes in water conditions from one day to the next	11
R_A9	6	D	Variability in reversals	Coefficient of variation in R_A8	11

The alphanumeric code refers to the category of the flow regime the hydrologic index was developed to describe, and indices are number successively within each category. For example, M_A1 is the first index describing the magnitude of average flow conditions. U refers to the units of the index: 1, $m^3\ s^{-1}$; 2, $1/m^3\ s^{-1}$; 3, $m^3\ s^{-1}\ km^{-2}$; 4, days; 5, $year^{-1}$; 6, dimensionless; and 7, $m^3\ s^{-1}\ d^{-1}$. T refers to the temporal aspect of the hydrograph that the hydrologic index represents: daily (D), monthly (M), or annual (A).

[a] 1, Clausen and Biggs (1997); 2, Clausen and Biggs (2000); 3, Clausen *et al*. (2000); 4, Hughes and James (1989); 5, Poff and Ward (1989); 6, Poff (1996); 7, Puckridge *et al*. (1998); 8, Richards (1989, 1990); 9, Richter *et al*. (1996); 10, Richter *et al*. (1997); 11, Richter *et al*. (1998); 12, Wood *et al*. (2000).

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